

THERMAL MASS FLOW SENSOR SIMILARITY THEORY – COMPARISON WITH EXPERIMENTS

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Abstract - A similarity theory was previously proposed for the thermal mass flow sensor to describe the nonlinear relationship among the sensor output, the gas flow rate, and the gas thermal-physical properties. In a compact form, the theory expresses the ratio of the sensor output to the gas thermal conductivity, S/k , as a function of the Péclet number of the flow in the sensor tube in a compact form. In the present paper, the similarity theory is further compared against experimental data collected from various semi-conductor process gases using mass flow controllers equipped with constant-temperature capillary thermal mass flow sensors. The similarity theory was primarily confirmed by scaling the live-gas data using gas thermal-physical property constants listed in common physics and chemistry handbooks. Minor discrepancies between the experimental data and the theory are associated with: (1) the simplifying approximations made in deriving the heat transfer mathematical theory leading to the similarity model; and (2) uncertainties in the gas thermal-physical property constants used for the data analysis. For practical applications these discrepancies were compensated by adjusting the gas specific-heat and thermal-conductivity coefficients by using two multiplying constants, e_c and e_k respectively, until the theory and the data match to within tight tolerances. Among the 20 or so semi-conductor process gases tested, the established multiplying constants are all fairly close to 1, suggesting that the current thermal-mass flow sensor theory is sound. Although the original similarity theory was developed for the constant-temperature thermal mass flow sensors, an argument is provided to show that the theory might also be used to explain the operation of a constant-current thermal mass flow sensor and its gas conversion factors.

INTRODUCTION

Thermal mass flow controllers have been widely adopted for measuring and controlling the flow of gases in various chemical processes. As shown in Fig. 1, a typical mass flow controller (MFC) consists of a thermal mass flow sensor, a laminar flow bypass installed in parallel to the sensor, a control valve, and the electronic control and communication circuit.

The thermal mass flow sensor (Fig. 2) consists of a metal sensor tube, over which two temperature sensitive resistance elements are installed. The resistors on the sensor tube have relatively large positive temperature-coefficient and they serve simultaneously as the heating and the sensing device. When there is no fluid flow, the excitation current going through the two resistance elements heats up the sensor tube in a symmetrical manner. When there is flow, the upstream resistor is cooled down by the entering fluid flow more than the downstream resistor experiences. In a constant-temperature sensor electronic drive circuit, the two resistors are individually powered by two separate voltage-sources until each reaches a predetermined temperature, and the change in power input to the two coils is used as an indicator for the gas flow rate. In a constant-current sensor electronic drive circuit, the two resistors form one branch of a Wheatstone bridge, and the voltage imbalance in the Wheatstone bridge due to the temperature difference between the two resistors is used as an indication of flow.

The capacity of a typical thermal mass flow sensor when used alone is rather limited. A typical industrial mass flow sensor measures up to about 10 sccm of nitrogen only. In order for the mass flow controller to be useful for controlling larger amounts of gas flow, a laminar flow bypass element is

frequently installed in parallel to the sensor. The laminar flow element acts essentially as a flow splitting device so that only a small fraction of the total flow goes through the sensor. The split ratio between the sensor and the laminar flow element depends on the design of the flow path. For laminar flow bypasses comprised of circular tubes of equal length and equal inside diameter to those of the tubular sensor, the split ratio is essentially equal to the bypass tube count multiplied by the ratio of the gas viscosity in the sensor to that in the bypass element, and the split ratio is approximately a constant independent of flow rate.

The industry's standard practice has been to calibrate the MFC with an inert gas, such as nitrogen, at a flow rate equal to the desired process gas flow-rate multiplied by a so-called gas correction factor or gas conversion factor. The gas conversion factor is a gas-dependent constant, typically identified as the ratio of the specific heat of nitrogen to that of the process gas of interest. Unfortunately the thermal mass flow sensor is a rather nonlinear device, and the conversion factor method is not very accurate except for very low flow rates.

A similarity theory was presented in [1] for the constant-temperature type of thermal mass flow sensors. Based on convection heat transfer theory, the similarity theory showed how the sensor output may be related to the gas flow rate by using the similarity principle after scaling the two variables using the gas thermal-physical properties. Furthermore, it also showed that in the linear range the process gas flow rate is indeed related to the calibration gas flow rate by the conventional gas conversion factors used expansively by the industry.

The sensor similarity theory was satisfactorily compared in [1] against experimental data obtained from several inert gases. Since then additional experiments involving a much wider selection of chemicals were performed to further validate the similarity theory. The experimental data and the related test techniques are presented below.

SENSOR SIMILARITY MODEL

The similarity theory for the constant temperature thermal mass flow sensor in [1] reads:

$$\frac{S}{k} \propto W \{Re_D \cdot Pr\} = W \left\{ \frac{\rho V D c_p}{k} \right\} \quad (1)$$

where S is the output from the constant temperature sensor, k is the gas thermal conductivity, ρ is the gas density, V is the flow speed, D is the tube inside diameter, and c_p is the gas specific heat. W represents a certain function characteristic of the sensor design. Re is the Reynolds number, Pr is the Prandtl number, and their product $RePr$ is the Péclet number of the flow.

The similarity model was validated in [1] against data collected from 8 inert gases including N₂, He, Ar, CO₂, CF₄, CH₄, CHF₃, and SF₆. These earlier tests were performed using constant-temperature thermal mass flow sensors with a tube ID of 0.0135 inches and a heated length of 0.5 inches. The heated portion of the tube was covered by two resistance coils symmetrically located and each maintained at 100 °C. A DryCal ML-500 piston prover with 1% of reading accuracy usable over 3-500 sccm flow rate was employed as the flow standard.

To re-iterate, Fig. 3 shows the sensor output electric signal plotted against the flow rate for the 8 inert gases previously tested. These data were re-plotted in Fig. 4 by using the non-dimensional quantities suggested by Eq. (1) above. In Fig. 4 gas property constants at an average temperature of 85 °C were used for calculating the dimensionless quantities. The quantity $Re_L Pr = Re_D Pr (L/D)$ was used in Fig. (4) for the horizontal axis instead of $Re_D Pr$. This is not a problem because L/D is a constant for the sensors under test. As shown in Fig. 4, although the $S/k \sim Re_L Pr$ curves from all 8 different gases collapsed into a narrow band, some of the curves in Fig. 4 do noticeably deviate from

each other at the higher flow rates. The departure of the curves was attributed to: (1) the various simplifying assumptions made in deriving the similarity model; and, (2) the uncertainty in the gas thermal-physical property data available. For practical applications, the correlation was improved in [1] by adjusting the gas specific heat by a multiplier e_c and the thermal conductivity by a multiplier e_k , and the results improved significantly as shown in Fig. 5.

MODEL VALIDATION - MASS FLOW CONTROLLERS

The flow standard DryCal ML-500 used in the sensor validation test above is only suitable for testing non-corrosive gases. In order to verify the theory against any semiconductor process gases that are corrosive or toxic, gravimetric test methods were developed. Fig. 6 shows the setup used for the gravimetric test for this study.

As shown in Fig. 6, the process gas contained in the source bottle is connected to the inlet of the mass flow controller. Downstream of the MFC is a three-way valve that directs the flow into either the sink or the sample bottle. Before the test, the sample bottle is vacuum-purged and weighed and then reconnected to the plumbing. Then the sink and the sample bottles are both immersed in liquid-N₂ and maintained at a temperatures of -195°C during the test. Right before the run the source bottle and the isolation valves were all opened. With the three way valve directing the flow toward the sink bottle, the MFC is given a set-point and the flow is allowed to stabilize. Then a command is given to the three-way valve switching the flow over to the weighed sample bottle at the same time when the timer is started. The gas flow, the line pressure, the bottle temperature, and the MFC's indicated flow rate were continuously monitored during the test. After the pre-calculated test time elapsed, the three-way valve is switched back so the flow is directed back into the sink bottle, at the same time the sample bottle is closed and the timer stopped. After the test run is complete, the plumbing is carefully vacuum purged. The sample bottle is removed from the test setup and warmed up to the room temperature before re-weighing. Finally the mass collected is divided by the elapsed test time to obtain the mass flow rate in the sccm unit.

The capability of the gravimetric test method reported above is mainly limited by its lengthy test time. Due to the accuracy and the resolution of the weighing scale, plus the tare weight of the sample bottles, measurement uncertainty analysis requires a sample size of no less than 40 grams in order to achieve 0.25% of reading accuracy. Using BCl₃ as an example, let's consider gravimetric tests using the sensor alone. With a sensor full-scale flow at about 2.6 sccm BCl₃, corresponding to 0.0136 gm/min, it will take 49 hours to complete the sensor test at 100% full-scale alone, and it would take 8.1 days to complete a test at 25% of sensor full-scale flow. As such it is clearly impractical to conduct the sensor test directly with the gravimetric method. Instead, to verify the similarity theory for corrosive gases, gravimetric tests were performed by using MFC's composed of both the sensor and a laminar flow bypass. Mass flow sensors and tubular bypass elements of equal length and diameter provides an ideally constant split ratio [2]. For the BCl₃ example, an MFC for 200 sccm BCl₃ was built using a 0.014"ID sensor (1.5 inches long) and a bypass consisting of a bundle of 0.014" ID round tubes (also 1.5 inches long). Owing to the constant bypass split-ratio, which may be determined from testing with an inert gas such as N₂, the sensor flow rate may be easily deduced once the MFC's total flow rate is determined from the gravimetric test.

Different from the sensor only tests, which were conducted by directly monitoring the sensor output at various gas flow rate, the mass flow controller tests begin by first calibrating the MFC with N₂, where the sensor output and the N₂ flow rates reported by the flow standard were recorded by a computer. The sensor characteristic curve is then constructed in Fig. 7 (just like in Fig. 5) by using the variables S/k and Re_{Pr} . This characteristic curve is then interpolated (diamond symbols in Fig. 7) and the results are used to 'compute' the calibration information for BCl₃ by using its gas specific heat and thermal conductivity data available in common gas property databooks[3,4], [5]. The results of the computation are stored in the MFC's EPROM to serve as the BCl₃ calibration look-up table, and the MFC is now ready for the gravimetric test.

The diamond symbols in Fig. 8 shows the results of the gravimetric tests collected from ten (10) different semiconductor process gases. These results compared well against the MFC's desired setpoint flow. The errors observed are all within 0.5% of reading after the model constants e_c and e_k are dialed in. The model constants e_c and e_k derived from the gravimetric tests are included in Table 1 after the bypass ratio and the effect of viscosity are properly accounted for. As shown in Fig. 8, due to current limit in the sensor drive we used during the gravimetric tests, the MFCs were configured such that the sensors all operate at Re_{LPr} less than 3000 and output levels below 0.6.

As shown in Table 1, the value of the constants e_c and e_k required for model adjustments for the 19 gases tested are all very close to 1. This strongly suggests that for constant-temperature mass flow sensors the similarity model is valid. Minor exceptions are related to Cl_2 and $SiCl_4$, for which the adjustment for thermal conductivity (through e_k) exceeded 10%; and C_4F_6 (Hexafluoro Butadiene-1,3), for which the adjustment for heat capacity (through e_c) exceeded 10%. We suspect that the relative large c_p adjustment needed for C_4F_6 may be attributed to the uncertainty of the empirical formula used for estimating the gas specific heat. However, the fairly large amount of adjustment required for the thermal conductivity of Cl_2 and $SiCl_4$ remains unexplained.

GAS CONVERSION FACTOR REVISITED

In [1] the similarity model Eq.(1) was used to show that for a constant-temperature sensor

$$\frac{[dS / d \dot{m}]_{PG}}{[dS / d \dot{m}]_{N_2}} = \frac{(C_p)_{PG}}{(C_p)_{N_2}} \quad (2)$$

, where C_p is the specific heat of the gas.

Equation (2) suggests that, when the sensor output S/k is expressed as a function of the Péclet number, the sensitivity of the sensor to the flow rate for different gases may be simply related to each other through the ratio of their gas specific heat, even when the sensor output is nonlinear.

Furthermore, in the low-flow limit, and in particular in the linear range, Eq.(2) may be simplified to show that the volumetric flow rate of the process gas is indeed related to that of the calibration gas by the ratio of their molar specific heat, i.e.,

$$\frac{\dot{Q}_{N_2}}{\dot{Q}_{PG}} = \frac{M_{N_2} \cdot (C_p)_{PG}}{M_{PG} \cdot (C_p)_{N_2}} = \frac{(\hat{C}_p)_{PG}}{(\hat{C}_p)_{N_2}} \quad (3)$$

, where $\hat{C}_p$ is the *molar* specific heat of the gas.

These results are interesting because we now have a viable explanation for the gas conversion factors that has been in use by the industry for years. It is also intriguing that although Eq (3) is derived from studying the constant-temperature sensor, its form is very much the same as the empirical conversion factor method used for all thermal mass flow sensors, regardless of whether they are of the constant-current or the constant-temperature type. This makes one wonder whether the present theory may be somehow related to the operation of the thermal mass flow sensor in general and not merely limited to the constant-temperature sensors alone. To explore this possibility, let us compare a specific constant-current sensor with a constant-temperature sensor side by side as shown in Fig. 9.

Assume both sensor having identical and symmetrical thermal mechanical construction. When the gas flow rate is zero, as shown in Fig. 9a, for the constant-current sensor on the left, suppose we apply a current $I_1 = I_2 = I$ into both coils of the constant-current sensor. As a result the coil temperature reaches T_1 and T_2 in the two coils, respectively. Symmetry of the sensor requires, however, $T_1 = T_2 = T$.

Next let's consider the constant-temperature sensor on the right-half of Fig (9a). Under the same ambient conditions, when the gas flow rate is zero, suppose we apply currents I_1 and I_2 into the two coils of the sensor respectively. We adjust the currents I_1 and I_2 individually until the two coils both reach the same temperature T as in the constant-current sensor in the left-half of Fig. (9a). Provided that the two sensor drive circuits are perfectly isolated from each other, and because the temperature in the two coils are identical, symmetry of the sensor requires $I_1 = I_2$. Now since the sensor on the left and the sensor on the right have identical thermal mechanical construction, also since both are maintained at the same temperature T , we would expect $I_1 = I_2 = I$, which is the same current as in the constant-current case. This suggests that at least in the limit of zero flow rate, there is no difference between the operating conditions of the constant-current and the constant-temperature sensors.

At very-low but non-zero flow rates, as shown in Fig (9b-left), due to the cooling effect of the incoming gas the temperature of the upstream coil of the constant-current sensor drops only slightly; yet the temperature of the down-stream coil does not change any significant amount. To the first order, the overall temperature profile along the sensor tube is very similar to that in the constant-temperature sensor (Fig 9b-right). Since the tube temperature profile and the gas flow rate determines the rate of heat loss to the gas, at the same low flow rate the heat loss from the constant-current and from the constant-temperature sensor should be approximately equal. This leads us to surmise that, regardless of whether it is a constant-current or a constant-temperature sensor, in the limit of very low flow rate the heat transfer from the coil to the gas depends on the flow Péclet number in the same manner. Thus the conversion factor for the constant-current thermal mass flow sensors may also be explained by the similarity theory, at least in the low flow limit.

At much higher flow rates (Fig. 9c), the temperature profile of the constant temperature sensor (right) remains a constant. However, the temperature profile along the constant-current sensor (left) becomes drastically different. Totally different magnitude of heat transfer now exist between the coils and the gas in the two sensors. The constant-temperature approximation will no longer be appropriate for the constant-current sensors.

CONCLUSIONS

The similarity theory for a constant-temperature sensor is validated through live-gas tests by using a wide selection of semiconductor process gases. The general agreement between the theory and the test results is good, suggesting that the similarity theory is valid. The similarity model provides a plausible explanation for the gas-conversion factors.

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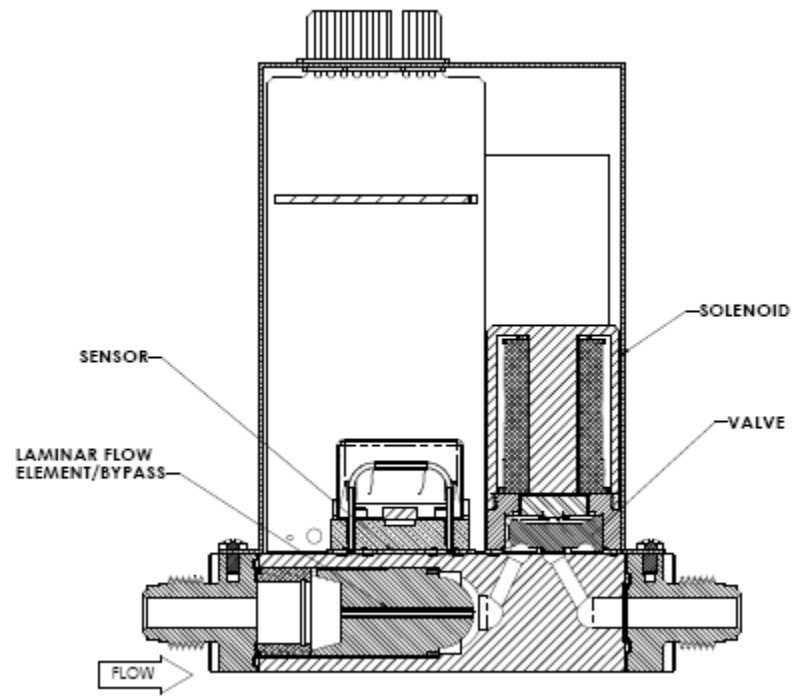


Fig. 1 Cross-sectional view of a Mass Flow Controller.

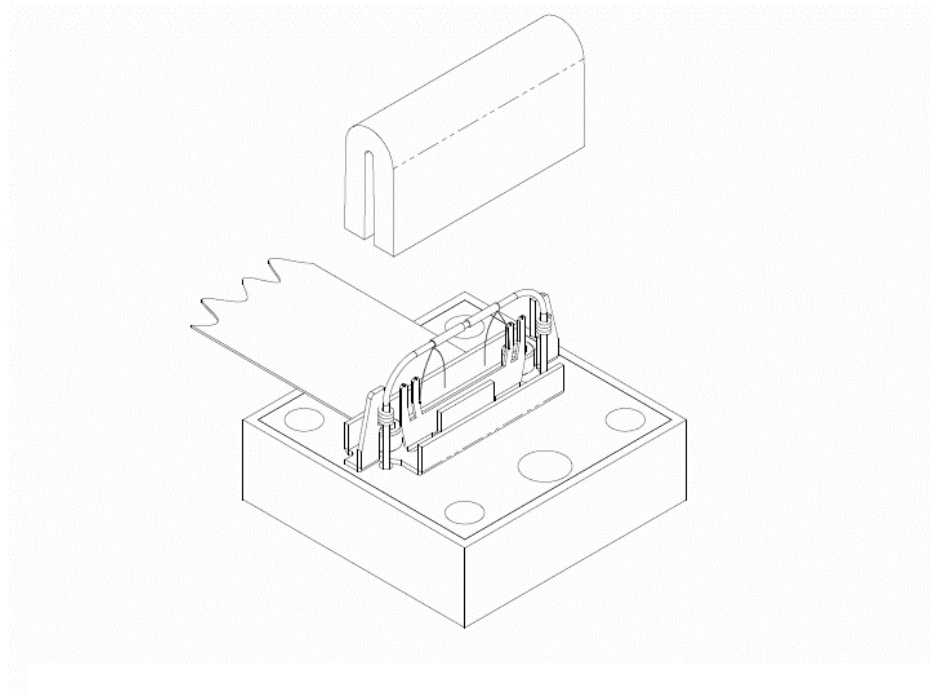


Fig. 2 Exploded view of a thermal mass flow sensor

Fig. 3 Sensor Response to Different Gas Flow

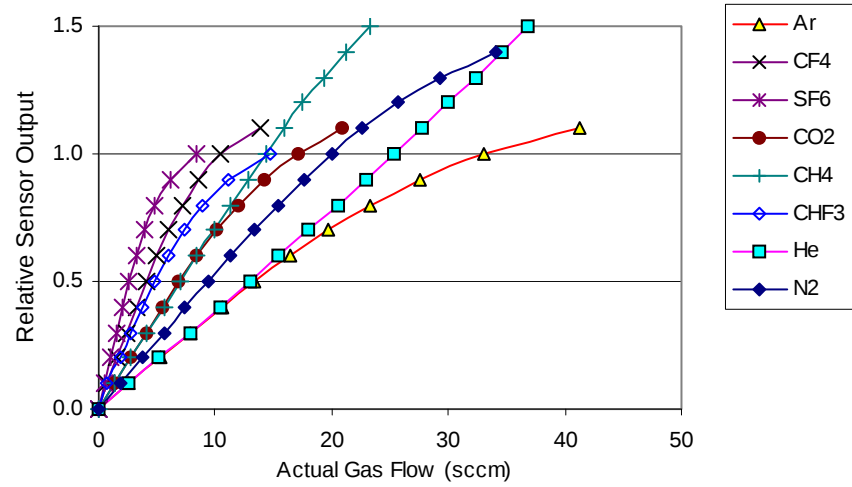
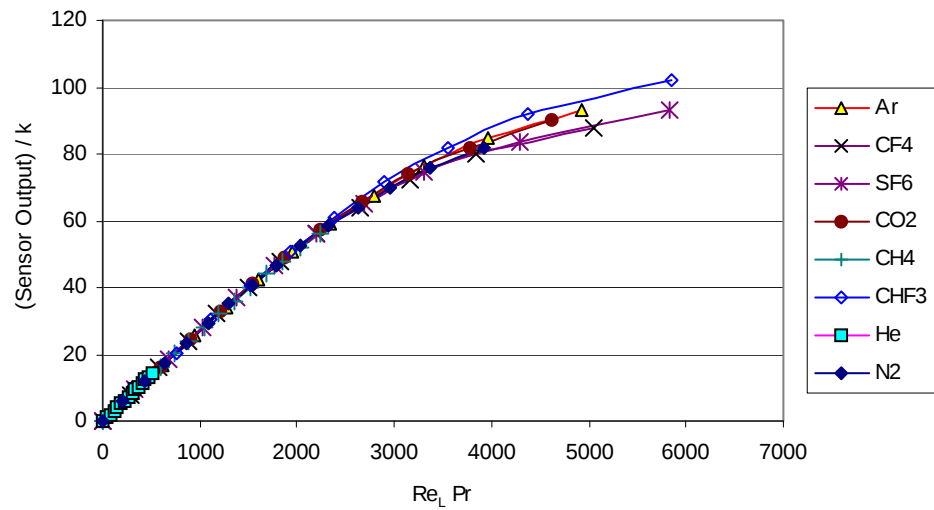


Fig. 4 Sensor Response Expressed in Similarity Variables



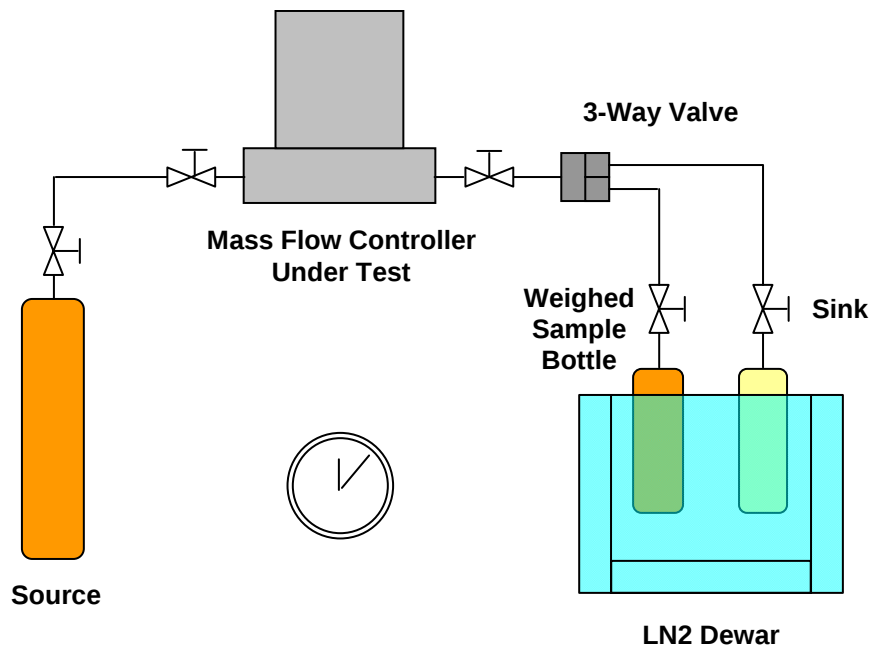
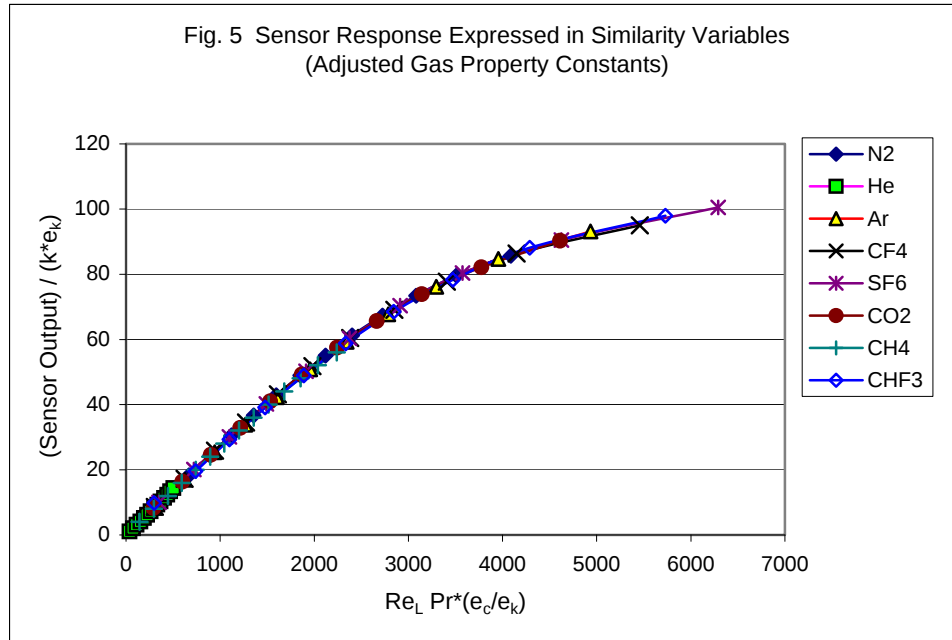
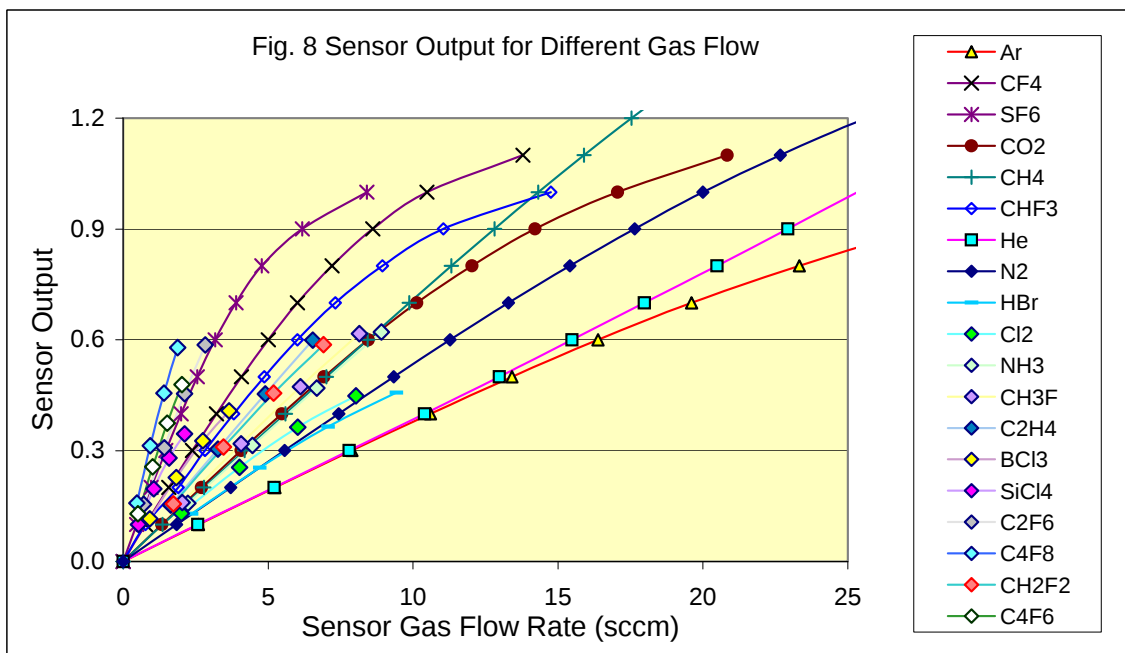
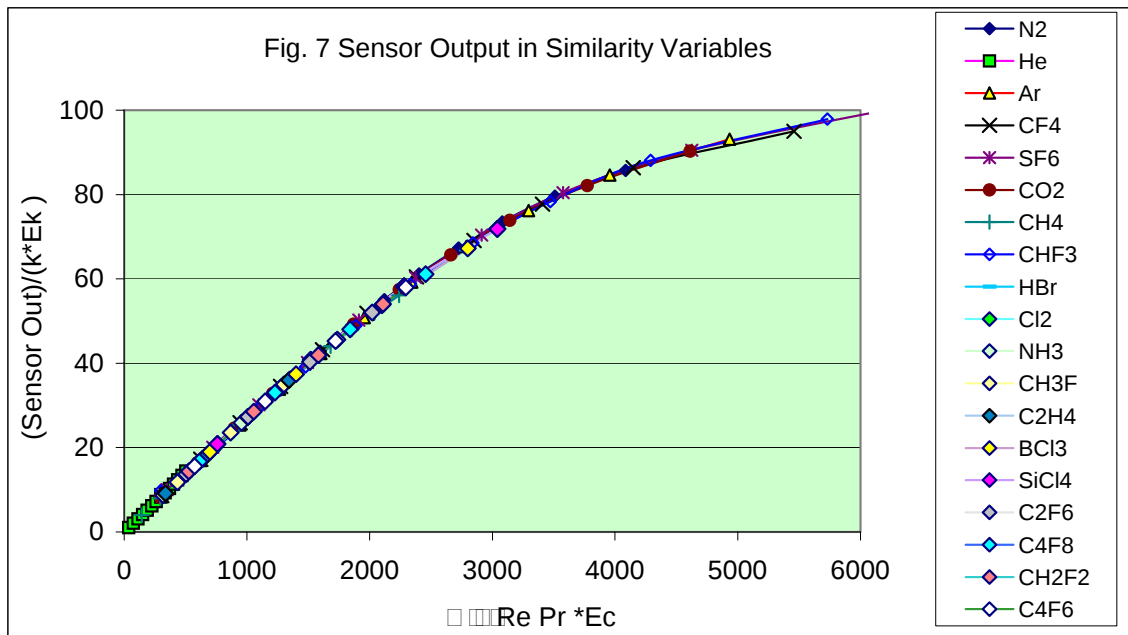
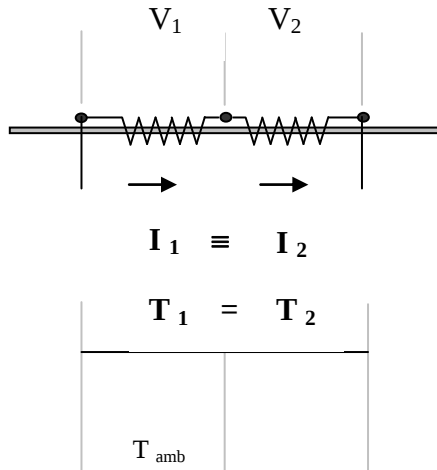


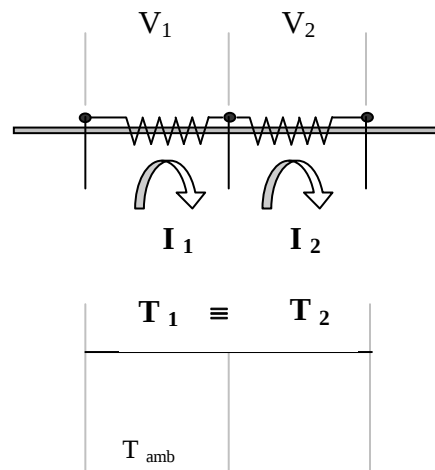
Fig. 6 Setup for testing process gases mass flow controllers gravimetrically by weighing.



Constant Current Sensor

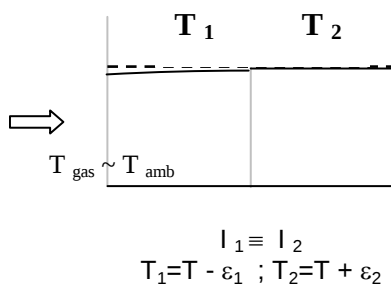


Constant Temperature Sensor

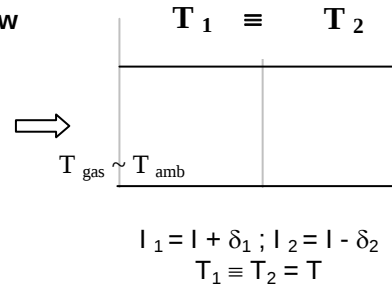


No Flow

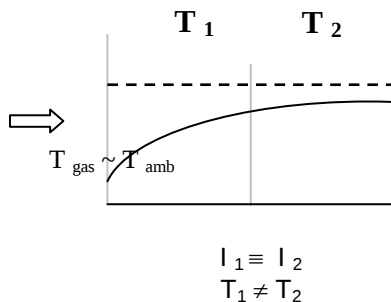
(a) No Flow – The constant current sensor is exactly the same as the constant temperature sensor, provided that the current is chosen to match T .



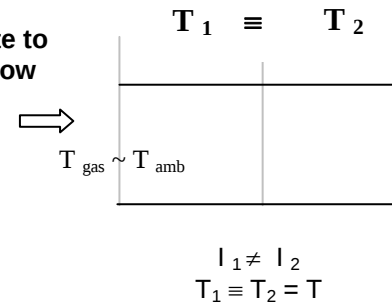
Very Low Flow



(b) Very Low Flow – The temperature profile and hence the heat transfer mechanism in the constant current sensor is not very different from that in a constant temperature sensor. Its sensor output ($T_1 - T_2$) may be shown to be proportional to the change in input power in the constant temperature sensor.



Moderate to High Flow



(c) Moderate to High Flow – The temperature profile and the heat transfer mechanism in the constant current sensor is drastically different from that in a constant temperature sensor.

Table 1 Values of e_c and e_k constants used in Fig. 5 and Fig. 7.

Gas	e_c	e_k
N2	0.99	0.95
He	1.00	1.00
Ar	1.00	1.00
CH4	1.00	1.00
CO2	1.00	1.00
CF4	1.00	0.93
CHF3	0.98	1.02
SF6	1.00	0.93
HBr	0.98	1.03
Cl2	0.99	1.15
NH3	0.98	1.0
CH3F	0.96	0.96
C2H4	0.97	0.98
BCl3	0.98	1.04
SiCl4	0.97	1.11
C2F6	0.98	1.00
C4F8	0.97	1.00
CH2F2	0.99	1.00
C4F6	1.15	1.00